



## Carbon storage and sequestration of re-growing montane forests in southern Ecuador



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### ABSTRACT

The storage and sequestration of carbon by tropical montane forests is poorly understood. We quantified the above-ground biomass (AGB) storage in secondary tropical montane forests in southern Ecuador. The AGB in older secondary (>40 years old) forest was found to be  $158 \pm 38 \text{ Mg ha}^{-1}$  of land surface at 1000 m elevation and  $104 \pm 25 \text{ Mg ha}^{-1}$  of land surface at 2250 m elevation. This is less than the storage reported in a recent synthesis of AGB observations in mature tropical montane forests, potentially due to a legacy of selective logging within our study sites. The slope angle resulted in AGB being 1.5–10% greater when reported on a planimetric compared to land surface area basis. We also quantified AGB in areas of abandoned pasture where grazing and fire had been excluded. Pasture that had been recently abandoned (1–2 years) stored 2–18  $\text{Mg ha}^{-1}$  of AGB with the higher values due to the presence of relict trees. Re-growing secondary forests, established through natural regeneration, accumulated AGB at a rate of  $10 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  at 1000 m elevation and  $4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  at 2250 m elevation, for the first 5–7 years after pasture abandonment. After 12–15 years, accumulation of AGB slowed to 1–2  $\text{Mg ha}^{-1} \text{ yr}^{-1}$ . Net biomass accumulation rates were similar to those observed in lowland humid tropical forests, suggesting that regenerating tropical montane forests provide an important carbon sequestration. In newly regenerating forests, small trees (DBH < 10 cm) contributed up to 50% of total AGB. In the older secondary forest at high elevation coarse dead wood contributed 34% of total AGB.

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### 1. Introduction

Tropical montane forests (TMF), defined here as forests between 23.5°N and 23.5°S above 1000 m.a.s.l., make up 8% of the world's tropical forests by planimetric area (Spracklen and Righelato, 2014). They are widely considered to be important for the provision of ecosystem services, especially water (Bruijnzeel, 2004) and biodiversity (Gentry, 1992; Mittermeier et al., 1999). Recent studies have also highlighted the potential for TMF to store and sequester substantial amounts of carbon (Fehse et al., 2002; Gibbon et al., 2010; Spracklen and Righelato, 2014). Here we report observations of above-ground biomass (AGB) storage within regenerating secondary TMFs in southern Ecuador.

The extent of carbon storage and sequestration in TMF is still relatively poorly understood. Spracklen and Righelato (2014) synthesised forest inventory data of AGB storage in TMF. They found that mean AGB in mature TMF was 271 Mg per hectare ( $\text{Mg ha}^{-1}$ )

of land-surface, declining with both slope and elevation. However, the steep slopes characteristic of TMF mean that on average TMF store 40% more AGB on a planimetric compared to a land-surface area basis (Spracklen and Righelato, 2014).

TMFs face threats due to deforestation and degradation (Doumenge et al., 1995; Tapia-Armijos et al., 2015) as well as from global climate change (Foster, 2001). The impact of forest degradation on AGB storage is not well understood. Lowland tropical forests in the Amazon that have been degraded by selective logging and understorey fires store 40% less AGB compared to undisturbed forests (Berenguer et al., 2014). Equivalent numbers for TMFs are rare or non-existent.

Secondary tropical forests are an important carbon sink and restoration of secondary forests can be an important climate change mitigation option (Locatelli et al., 2015). Silver et al. (2000) completed a meta-analysis of biomass sequestration in tropical forests, reporting AGB sequestration of  $6.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  during the first 20 years of succession. Biomass storage in secondary tropical forests returns to pre-disturbance values after 80 years (Martin et al., 2013). Rates of biomass accumulation in secondary forests are typically faster in regions with high

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surrounding forest cover (Bonner et al., 2013). However, the rate of biomass accumulation in secondary forests is poorly quantified in TMFs, with very few previous studies. Fehse et al. (2002) reported that newly (6–8 year) secondary TMF can sequester AGB at a rate of up to  $15 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ . Gilroy et al. (2014) found that non-soil carbon stocks accumulated at a rate of  $4.3 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  in naturally regenerating montane forests in Columbia. Fast rates of carbon sequestration would make restoration of TMF an important contributor to carbon removal from the atmosphere.

Our objectives in this study were to quantify the above-ground biomass storage in TMF in southern Ecuador and to determine how biomass stocks changed after clearance for agriculture and during recovery of secondary forests after agriculture ceased.

## 2. Methods

### 2.1. Study sites

Field work was carried out at two TMFs (Buenaventura and Tapichalaca) in southern Ecuador (Fig. 1). Both forests are owned and managed by the Ecuadorian non-governmental organisation, Fundacion Jocotoco (<http://www.fjocotoco.org>). The forests are managed with the primary aim of biodiversity protection. Both sites consist of secondary forest and pasture intended for forest regeneration. Secondary forests here are typically abandoned pasture undergoing natural regeneration. Abandoned pasture may account for 35% of total pasture area in montane regions of southern Ecuador (Knocke et al., 2014). Forests at both sites may have been selectively logged in the past. At each reserve we located forest plots in secondary forests of various ages.

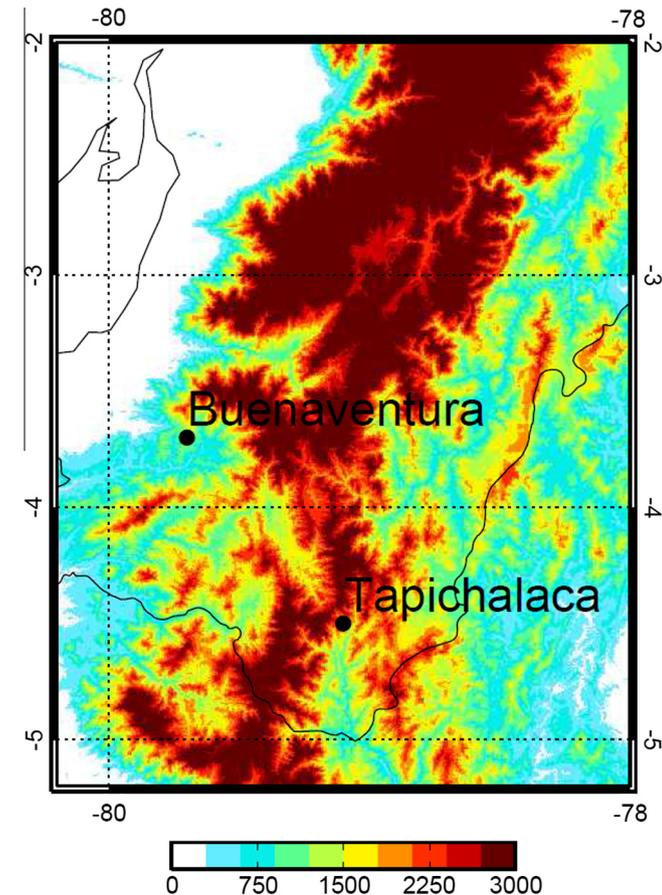


Fig. 1. Location of Buenaventura and Tapichalaca forest reserves. Background colour shows elevation (m.a.s.l.).

Buenaventura Reserve is located near the town of Pinas in the El Oro province of southern Ecuador ( $3.7^{\circ}\text{S}$ ,  $79.7^{\circ}\text{W}$ ). The reserve spans elevations between 400 m and 1200 m altitude on the Pacific slope of the Ecuadorian Andes. Land use in the reserve was at least 90% secondary forest, with very little primary forest remaining. A road that was built through the area in the 19th Century to provide access for machinery for gold mining in the area likely brought about selective logging (N. Simpson, personal communication). In 2011, the reserve covered an area of about 2000 ha. At 1075 m m.a.s.l., annual mean temperature is  $22.5^{\circ}\text{C}$  and annual mean rainfall is  $1475 \text{ mm yr}^{-1}$  (Hijmans et al., 2005).

Tapichalaca Reserve is located on the east slope of the Andes adjacent to the Podocarpus National Park ( $4.5^{\circ}\text{S}$ ,  $79.1^{\circ}\text{W}$ ). The reserve spans elevations from 2000 to 3400 m and is about 2000 ha in size. The region is characterised by steep slopes and a high frequency of natural landslides (Moser et al., 2008). At 1900 m a.s.l., annual mean temperature is  $18.7^{\circ}\text{C}$  and annual mean rainfall is  $1250 \text{ mm yr}^{-1}$  (Hijmans et al., 2005). At the nearby Podocarpus National Park, annual mean temperature (inside the forest, 1.5 m height) decreases from  $18.9^{\circ}\text{C}$  at 1050 m to  $8.6^{\circ}\text{C}$  at 3060 m, while rainfall increases with elevation from  $1950 \text{ mm yr}^{-1}$  at 1980 m to  $4500 \text{ mm yr}^{-1}$  at 3060 m (Leuschner et al., 2007). The tree line is typically at 3300–3500 m elevation in the region. Human settlement in the region in the middle of the 20th century likely resulted in selective logging and the extraction of the largest trees.

### 2.2. Field method

Data was collected during a 3 month period from June through August 2005. We classified each reserve into areas of secondary forest and pasture. Secondary forest existed on areas of abandoned pasture, with forest re-establishing through natural regeneration. We identified areas of secondary forest with ages of 1–15 years since cessation of grazing and burning. The land-use history of each site was determined through interviews with forest guards employed at the reserve. Only areas where at least two forest guards gave a consistent land-use history (estimates of time since abandonment of pasture within 20% of each other) were included in the study. The oldest secondary forest plots were located where there was no visual evidence of human disturbance or landslide activity and no knowledge of clearance within the past 40 years. These plots have secondary forests that are at least 40 years old. Selective logging may historically have occurred in these plots and so they should not be referred to as mature or primary forests. Landslides occur frequently on moderate to steep slopes within the region (particularly at Tapichalaca) and are likely to play a key role in controlling the carbon balance of the forest. However, for the purposes of this work we did not sample areas where landslides were known to have occurred.

Plot establishment and measurement followed the RAINFOR (Red Amazonica Inventarios Forestales, Amazon Forest Inventory Network) guidelines (<http://www.geog.leeds.ac.uk/projects/rainfor/index.html>; Malhi et al., 2002). One hectare plots ( $10,000 \text{ m}^2$  surface area, square  $100 \text{ m} \times 100 \text{ m}$ ) were located randomly in secondary forests of different ages (Table 1). The location of plots was identified using GPS. The location, slope and elevation of each plot were recorded. Four secondary forest plots were measured in Buenaventura with ages of 1, 5, 12 and  $>40$  years. Three secondary forest plots were established at Tapichalaca with ages of 2, 15 and  $>40$  years. The  $>40$  year old forest plots at both Buenaventura and Tapichalaca had no known anthropogenic disturbance within the last 40 years and were at least 40 years old.

Biomass was estimated using a non-destructive method. Within each one hectare plot we measured the tree height and diameter at breast height (DBH, 1.3 m above-ground on the uphill side of stem)

**Table 1**  
Age and altitude of forest plots.

Forest age (years)	Altitude (m)
<i>Buenaventura</i>	
1	550
5	515
12	535
40	1035
<i>Tapichalaca</i>	
2	2250
15	2250
40	2250

of all trees with a DBH greater than 10 cm. The genus of each tree was recorded where this could be identified and trees were tagged with a numbered metal plate at 1.6 m. Location of the trees within the plot was recorded. Lauraceae, Melastomataceae and Rubiaceae were the most frequent tree families recorded at both locations. We measured coarse woody debris (CWD) following the method of Wilcke et al. (2005). Dead wood, standing dead trees and tree stumps were treated as CWD.

Each plot was divided into 20 m × 20 m (400 m<sup>2</sup>) sub-plots. Five of the sub-plots were selected and within these plots the DBH, tree height and genus of all trees with DBH greater than 2.5 cm was measured. Understorey and ground litter biomass was determined in 1 m<sup>2</sup> plots in each sub-plot. All living and dead vegetation with DBH less than 2.5 cm was collected and weighed in the field. Superficial soil samples (0–5 cm in mineral soil) were taken from each plot.

### 2.3. Estimation of biomass

We estimated the biomass in above-ground, below-ground within roots and in CWD. We did not attempt to quantify soil carbon. Understorey and ground litter biomass was not been analysed due to problems with effectively drying biomass samples. In upper-montane forests in Podocarpus National Park, Ecuador, litter has been found to contribute 3–8 Mg biomass ha<sup>-1</sup> (Leuschner et al., 2013).

We estimated AGB using existing allometric equations. Allometric equations specific to tree family are currently not available for montane forests in Ecuador so generic allometric equations (Brown, 1997; Chave et al., 2005) were used. We used the allometric equation from Chave et al. (2005) for wet forests where AGB is as a function of tree height ( $H/m$ ), diameter at breast height ( $D/cm$ ) and wood density ( $\rho/g\text{ cm}^{-3}$ ):

$$AGB = \exp[-2.557 + 0.94 \ln(\rho \times D^2 \times H)]$$

Chave et al. (2004) make a detailed assessment of the errors associated with calculating AGB from forest plots and allometric equations. We estimate the error in our biomass values using the 24% error reported by Chave et al. (2004) for the combined error due to choice of allometric equation and sampling errors. Calculating AGB using Chave et al. (2005) for moist tropical forests changes our biomass estimates by less than 17%; less than the error we assume in our AGB estimates.

For individual trees where tree height was not recorded it was estimated by fitting a regression between available height and DBH data for that location. We assumed a wood density of 0.571 g cm<sup>-3</sup>, the mean density reported by a study in TMF in Peru (Gibbon et al., 2010). This is approximately 10% lower than the mean wood density of 0.645 g cm<sup>-3</sup> reported by Chave et al. (2006) for 2456 tree species in Central and South America. We assumed that dry stem biomass consists of 50% carbon by mass (Chave et al., 2005).

Above-ground standing deadwood biomass was calculated in the same way as the AGB in living trees. For both standing deadwood and coarse woody matter we assumed a wood density of 0.31 g cm<sup>-3</sup> which was the average for coarse woody debris in a montane forest in Ecuador above 2000 m (Wilcke et al., 2005). Below-ground root biomass (fine and coarse roots) was calculated based on AGB according to Cairns et al. (1997):

$$BGB = \exp[-1.0587 + 0.8836 \ln(AGB)]$$

This approximates to about 20% of above-ground biomass, consistent with other studies (Leuschner et al., 2013; Moser et al., 2011).

We report AGB as storage per land surface ( $S$ ) area. We use angle of slope ( $\theta$ ) to calculate storage per planimetric ( $P$ ) area, using the following conversion:

$$S = P / \cos(\theta).$$

### 3. Results and discussion

The biomass storage (per land surface area) calculated at Buenaventura and Tapichalaca Forest Reserves are detailed in Table 2. In >40 year old forest plots we calculated AGB to be 158 ± 38 Mg ha<sup>-1</sup> in Buenaventura and 104 ± 25 Mg ha<sup>-1</sup> at Tapichalaca, where the error is estimated following Chave et al. (2004). When reported on a planimetric area basis, AGB is 1.5% greater at the forest plot in Buenaventura (slope angle 10°) and 10% greater in the forest plot at Tapichalaca (slope angle 25°).

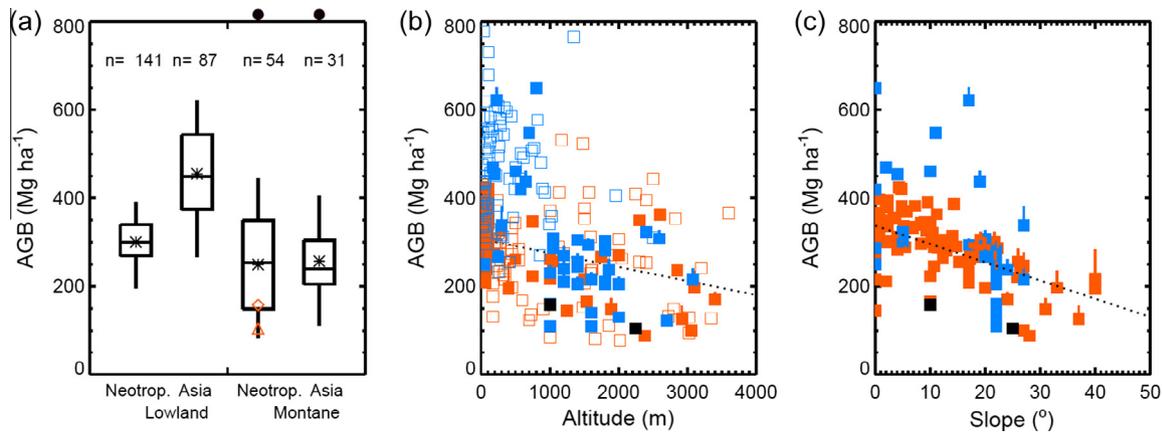
Fig. 2 shows a comparison of total AGB in >40 year old forest plots in Buenaventura and Tapichalaca compared to a mature TMF (Spracklen and Righelato, 2014). The AGB in both Buenaventura and Tapichalaca is less than mean (271 Mg ha<sup>-1</sup>) and median (254 Mg ha<sup>-1</sup>) reported for all TMFs in Spracklen and Righelato (2014). Values reported here are also lower than the mean (247 Mg ha<sup>-1</sup>, 1σ = 115 Mg ha<sup>-1</sup>) and median (241 Mg ha<sup>-1</sup>) values for Neotropical montane forest sites. In Buenaventura, estimated AGB is in the 25th to 50th percentile of Neotropical TMFs reported by Spracklen and Righelato (2014). In Tapichalaca, AGB

**Table 2**

Biomass storage in Buenaventura (B) and Tapichalaca (T) Reserves. Biomass is reported as storage per hectare of land surface.

		Forest age (years)			
		1–2	5	12–15	>40
Tree (DBH > 10 cm) density (stems ha <sup>-1</sup> )	B	18	104	421	594
	T	71	–	396	503
Sapling (2.5 cm < DBH < 10 cm) density (stems ha <sup>-1</sup> )	B	130	1830	305	1145
	T	975	–	–	1365
Above-ground biomass (brown; DBH > 10 cm) (Mg ha <sup>-1</sup> )	B	1.3	24.0	89.4	98.5
	T	8.7	–	57.2	65.3
Above-ground biomass (Chave et al., 2005, moist; DBH > 10 cm) (Mg ha <sup>-1</sup> )	B	1.0	28.6	128.8	134.1
	T	7.0	–	48.5	57.2
Above-ground biomass (Chave et al., 2005, wet; DBH > 10 cm) (Mg ha <sup>-1</sup> )	B	1.0	24.3	106.9	121.8
	T	6.8	–	44.9	53.5
Above-ground biomass (2.5 cm < DBH < 10 cm) (Mg ha <sup>-1</sup> )	B	1.7	17.6	1.6	11.6
	T	9.2	–	10.1	15.1
Below-ground root biomass <sup>a</sup> (Mg ha <sup>-1</sup> )	B	0.9	9.4	21.8	26.2
	T	4.0	–	12.0	14.6
Dead wood biomass (Mg ha <sup>-1</sup> )	B	0	0	1.7	24.9
	T	2.3	–	16.6	35.8
Total biomass <sup>a</sup> (Mg ha <sup>-1</sup> )	B	3.6	51.2	131.2	184.5
	T	223	–	83.5	119.0
Total above-ground biomass <sup>a</sup> (Mg ha <sup>-1</sup> )	B	2.7	41.8	110.2	158.3
	T	18.3	–	71.6	104.5

<sup>a</sup> Calculated based on Chave et al. (2005) Wet forest for DBH > 10 cm.



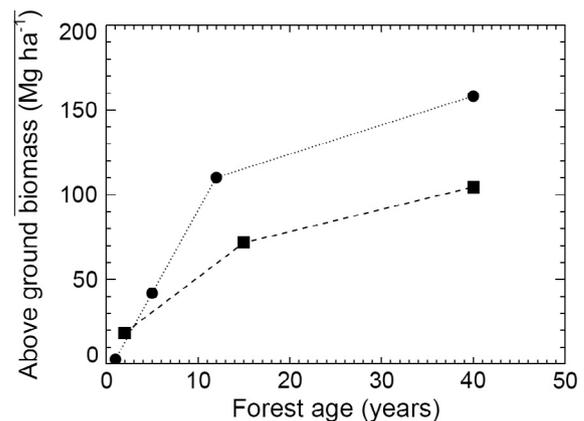
**Fig. 2.** Above-ground biomass (AGB) storage estimated from forest inventory plots. (a) Comparison of AGB (on a land surface area basis) in the 40 year old forest plots in Buenaventura (red diamond) and Tapichalca (red triangle) against the data on tropical montane forests (elevation > 1000 m) and lowland tropical forests reported in Spracklen and Righelato (2014) (excluding data from sites reported here; star: mean, line: median, box: 25th and 75th percentile, whisker: 5th and 9th percentile). Significant differences between lowland and montane (Student's *t* test,  $P < 0.01$ ) indicated by a solid circle above panel. (b) Relationship between AGB and elevation (neotropics: red, Asia: blue). Open symbols show sites where no information on slope is available. (c) Relationship between angle of slope and AGB. In (b) and (c), symbols show AGB per land surface area (linear relationship for the neotropics is shown with a dotted line), tops of bars show AGB per planimetric area. Black squares show data from Buenaventura and Tapichalca. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is less than the mean minus one standard deviation ( $1\sigma = 115 \text{ Mg ha}^{-1}$ ) and is in the 5th to 25th percentile reported by Spracklen and Righelato (2014). Compared to other Neotropical montane forests, AGB in Buenaventura and Tapichalca is low both with respect to elevation (Fig. 2b) and slope angle (Fig. 2c).

Our estimates of AGB are less than some previous estimates of TMFs in the Ecuadorean Andes, for example  $241 \text{ Mg ha}^{-1}$  for 45 year old *Alnus* forest;  $366 \text{ Mg ha}^{-1}$  for 30 year old *Polylepis* forest at 3200–3600 m altitude (Fehse et al., 2002). However, values reported for plots in the Podocarpus National Park:  $99 \text{ Mg ha}^{-1}$  in similar mixed forest at 2380 m and  $112 \text{ Mg ha}^{-1}$  in elfin forest at 3060 m (Moser et al., 2011), were similar to the  $104 \text{ Mg ha}^{-1}$  that we measured for >40 year old forest at Tapichalca, which is nearby. It is possible that low AGB at both sites is a legacy of historical selective logging. Selective logging would have resulted in the extraction of the largest trees, which are the largest contribution to AGB in mature forest (Berenguer et al., 2014). Analysis of the distribution of DBH at both sites demonstrates relatively few large stems (DBH > 50 cm) which may be an indication of past selective logging. The >40 year old forest plots we measure here store 36–58% less AGB compared to the mean AGB storage of neo-tropical TMFs (Spracklen and Righelato, 2014). We suggest that it is likely that this lower AGB is at least partly due to a legacy of selective logging. In lowland tropical forests, secondary forests can store 40% less AGB compared to primary forests (Berenguer et al., 2014), consistent with the lower biomass storage we report for secondary TMF.

Fig. 3 shows above-ground biomass storage at both sites as a function of forest age. In Buenaventura, total AGB increased from  $2.7 \text{ Mg ha}^{-1}$  in recently abandoned pasture to  $158 \text{ Mg ha}^{-1}$  in >40 year old forest. In Tapichalca, total AGB increased from  $18.3 \text{ Mg ha}^{-1}$  in recently abandoned pasture to  $104 \text{ Mg ha}^{-1}$  in >40 year old forest. A greater number of relict trees in the recently abandoned pasture at Tapichalca resulted in AGB being greater than at Buenaventura.

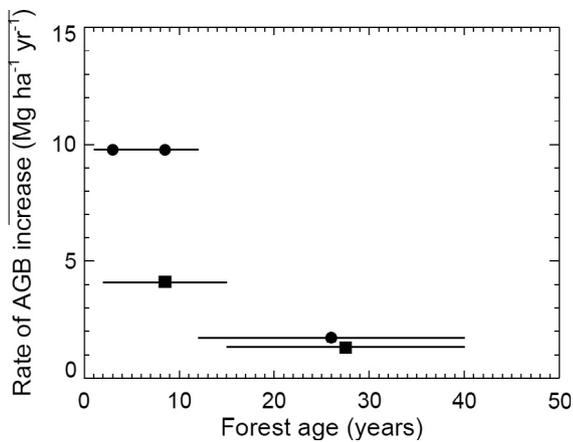
At Buenaventura, total (above ground and roots) biomass storage increases from  $3.6 \text{ Mg ha}^{-1}$  in newly abandoned pasture to  $185 \text{ Mg ha}^{-1}$  in >40 year old forest. At Tapichalca, total biomass increases from  $22.3 \text{ Mg ha}^{-1}$  in newly abandoned pasture to  $119 \text{ Mg ha}^{-1}$  in >40 year old forest. These values include an estimate of the biomass in roots but do not include soil biomass or soil carbon, which is reported to exceed the total above ground carbon at a nearby site in southern Ecuador (Leuschner et al., 2013).



**Fig. 3.** Above-ground biomass storage as a function of forest age (circles: Buenaventura, squares: Tapichalca).

Fig. 4 shows the calculated rate of AGB accumulation as a function of forest age. We calculate this rate as the difference in AGB storage between two forest sites divided by the difference in age between the two sites. We find that AGB accumulation is greatest in early stages of succession from pasture. In Buenaventura (1000 m.a.s.l.), the rate of AGB accumulation is  $9.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  between 1 and 5 years,  $9.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  between 5 and 12 years, falling to no more than  $1.7 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  between 12 and >40 years. At Tapichalca (2250 m.a.s.l.), the rate averaged  $4.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  between 2 and 15 years and no more than  $1.3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  between 15 and >40 years.

Fehse et al. (2002) calculated a time-averaged annual biomass accumulation (ABA) by dividing the AGB at a certain age by forest age for 17 Neotropical forest sites (this method includes the biomass present at time zero and so may overestimate net biomass accumulation). For ten young forest (4–8 year old) sites, the ABA averaged  $11.8$  ( $7.2$ – $16.3$ )  $\text{Mg ha}^{-1} \text{ yr}^{-1}$  falling to  $8.3$  ( $4.9$ – $13.5$ )  $\text{Mg ha}^{-1} \text{ yr}^{-1}$  for seven 15–20 year old sites. There was no significant difference between the lowland sites ( $n = 12$ ) and montane sites ( $n = 4$ ). Calculated in the same way, the ABA we observed were similar:  $8.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  at 5 years and  $9.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  at 12 years at Buenaventura, and  $4.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  at 15 years at Tapichalca.



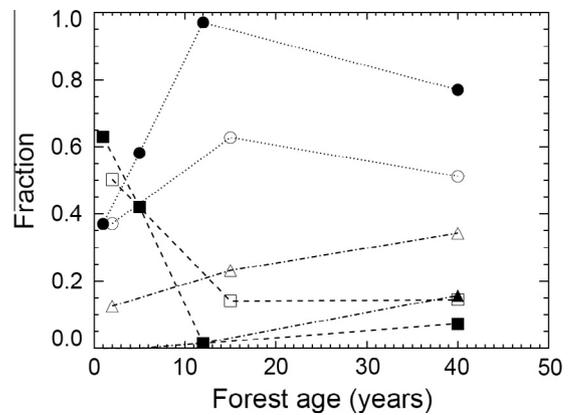
**Fig. 4.** Average rate of biomass carbon accumulation as a function of secondary forest age (Tapichalaca Forest Reserve: squares, Buenaventura Forest Reserve: circles). Horizontal lines indicated the time over which average is calculated.

Rapid carbon accumulation in montane forests has been observed previously: [Fehse et al. \(2002\)](#) attributed rapid biomass accumulation to rapid sapling establishment and fast growth rate. Rapid regeneration of forests on disturbed sites has also been reported previously ([Fehse et al., 2002](#); [Scatena et al., 1996](#); [Uhl and Jordan, 1984](#)) but is dependant on site conditions and history ([Knoke et al., 2014](#)) and can be inhibited in sites that have been severely impacted by heavy grazing ([Sarmiento, 1997](#)). At the sites surveyed here, removal of grazing pressure was sufficient to allow sapling establishment and rapid accumulation of biomass.

To estimate the regional carbon sequestration by areas of abandoned pasture in southern Ecuador (Loja and Zamora Chinchipe Provinces) we combined information of the area of pasture in the region (1218 km<sup>2</sup>) from [Tapia-Armijos et al. \(2015\)](#), with an estimate of the fraction of pasture that has been abandoned (35%) from [Knoke et al. \(2014\)](#). This suggests that there is ~426 km<sup>2</sup> of abandoned pasture in the region. Combining this area with our estimate of biomass accumulation in areas of recently abandoned pasture (using the range of 4–10 Mg ha<sup>-1</sup> yr<sup>-1</sup>) suggests a regional carbon sequestration of 85260–213 150 Mg C yr<sup>-1</sup> (assuming biomass is 50% carbon).

**Fig. 5** shows the fraction of total biomass in different carbon pools as a function of forest age. Biomass stored in small trees (2.5 cm < DBH < 10 cm) made a considerable contribution to total carbon storage in young secondary forests (up to 50%) with a smaller contribution (<15%) in >40 year old forest. The importance of coarse woody debris (CWD) as a carbon store increased with forest age and with altitude, being 34% of total biomass storage for the >40 year old forest site at 2250 m elevation. Our estimates for the biomass stored in CWD in older secondary forests (25 and 35 Mg ha<sup>-1</sup>) were greater than those previously recorded by [Wilcke et al. \(2005\)](#) in Southern Ecuador (0.4–23 Mg ha<sup>-1</sup> with a mean of 9.1 Mg ha<sup>-1</sup>, for forests at 1900–2180 m elevation).

Our below-ground root biomass estimates (21 Mg ha<sup>-1</sup> for >40 year old forest at 1000 m elevation) are consistent with detailed observations of root biomass in the Ecuadorean Andes of 28 Mg ha<sup>-1</sup> at 1900 m, 40 Mg ha<sup>-1</sup> at 2400 m and 68 Mg ha<sup>-1</sup> at 3000 m ([Soethe et al., 2007](#)). Our root carbon estimates are calculated using regressions based on the AGB value that do not include an effect of altitude. Our root biomass estimations at ~2250 m altitude are about a quarter of the values observed by [Soethe et al. \(2007\)](#), suggesting that we may under-predict root carbon biomass at the higher altitude sites.



**Fig. 5.** Fraction of total above ground biomass within different carbon pools (woody biomass, DBH > 10 cm (circles), woody biomass DBH 2.5–10 cm (squares), coarse woody debris (triangles)) as a function of forest age in Buenaventura (closed symbols) and Tapichalaca (open symbols). Lines join points to guide the eye.

#### 4. Conclusion

We report on measurements of carbon storage in re-growing tropical montane forests in Ecuador. We analysed seven one hectare secondary montane forest plots in Southern Ecuador for above-ground biomass storage. The plots spanned a variety of forest ages from recently abandoned (1 year old) pasture to older secondary (at least 40 year old) forest. Older secondary forests were identified as areas where there was no visible sign of human disturbance or land slide activity and where there was no known human disturbance within the last 40 years. Above-ground biomass storage in the >40 year old forest plots varied between 104 (at 2250 m elevation) and 158 Mg ha<sup>-1</sup> of land surface (at 1000 m elevation). On a planimetric area basis, above-ground biomass storage was 1.5% greater at 1000 m elevation and 10% greater at 2250 m elevation. The biomass storage reported here in >40 year old secondary forests is towards the lower end of that in previously studied tropical montane forests ([Spracklen and Righelato, 2014](#)). It is possible that historical selective logging occurred at both sites removing the largest trees and reducing the biomass values reported here. Above-ground biomass storage in recently abandoned (1–2 year old) pasture was 2–18 Mg ha<sup>-1</sup>, with the larger value due to a greater number of relict trees that survived deforestation and pasture development. Biomass accumulation during the natural succession of pasture to secondary forest was rapid for the first 12–15 years being 10 Mg ha<sup>-1</sup> yr<sup>-1</sup> at 1000 m elevation and 4 Mg ha<sup>-1</sup> yr<sup>-1</sup> at 2250 m elevation. In our study natural regeneration was sufficient to establish secondary forest on areas on abandoned pasture, without the need for additional tree planting. Net biomass accumulation rates in our montane sites were similar to those observed previously in lowland humid tropical forests. The large areas of abandoned montane pasture in southern Ecuador ([Knoke et al., 2014](#); [Tapia-Armijos et al., 2015](#)) means that reforestation and restoration of could sequester substantial amounts of carbon. Overall, our results suggest that reforestation and restoration of tropical montane forests should be considered as an important climate mitigation option.

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